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Daeng-Am, W., Chureemart, P., Chantrell, R. W. orcid.org/0000-0001-5410-5615 et al. (1 more author) (2019) Granular micromagnetic model for perpendicular recording media : Quasi-static properties and media characterisation. Journal of Physics D: Applied Physics. 425002. ISSN 0022-3727

https://doi.org/10.1088/1361-6463/ab33d6

Granular Micromagnetic Model for Perpendicular Recording Media: Quasi-Static Properties and Media Characterisation

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May 2019

Abstract. Granular magnetic recording media with perpendicular anisotropy are the basis of information storage in hard drive. This is the case for current media and future technologies such as heat assisted magnetic recording (HAMR), microwave assisted magnetic recording (MAMR) and heated dots. It is therefore important to understand the common methods of media characterisation, which often use quasi-static magnetic measurements. A granular micromagnetic model based on the kinetic Monte Carlo (kMC) approach is developed to investigate the timescales relevant to these measurements. The model is used to investigate the effects of the microstructure and the intergranular interactions on the magnetic properties including the angular dependence of the magnetisation and the time dependence of the coercivity. The latter is shown to be strongly dependent on intergranular interactions.

Keywords: kinetic Monte Carlo, intergranular exchange interaction, switching field distribution, easy axis distribution.

1. Introduction

Magnetic recording media remain the dominant form of long-term information storage, nowadays concentrated in data centres. The current rapid increase in the generation of business and personal data fuels the requirement for increased data density on individual drives. The increased density is achieved via a scaling process involving reduction of the grain size of the storage medium in order to preserve signal to noise ratio. This leads to the requirement of increased magnetic anisotropy in order to ensure long-term thermal stability of the written information which necessitates a minimum value of the stability parameter $K_U V/k_B T = 60$ where, K_U is the uniaxial anisotropy, V is the grain volume, k_B is the Boltzmann's constant and T is the temperature. The well-known recording trilemma is completed by noting that the write-field required increases with K_U. Reducing magnetic grain size (D<7 nm [1, 2, 3]) leads to improved performance, but current systems, based on perpendicular magnetic recording (PMR) technology, are already approaching the limiting densities imposed by the trilemma, given that write-fields are limited to around 1T or less using conventional inductive technology. Further, the dimensions of the writer is also limited [4]. Moreover, the limited field resolution and gradient provided by the narrower shielded-pole writer for PMR can be one source of noise in the medium [5]. Current PMR media are widely based on CoPt [1, 3, 6].

Future magnetic recording technologies will need to circumvent the trilemma. The two main candidates, essentially energy-assisted techniques, are: Heat Assisted Magnetic Recording (HAMR), where laser heating is used to lower the switching field of the medium [7, 8], and Microwave Assisted Recording (MAMR) where the writing process is assisted by using an ac magnetic field at microwave frequencies generated from a spin torque oscillator [4, 9]. While MAMR could be used with current media types, HAMR adds the requirement of a low Curie temperature (T_c) so as to avoid excessive heating of the recording medium. Currently the most likely candidate for HAMR is the binary alloy FePt, which combines the requirements of large K_U and low T_c. Thus, current and future recording systems cover a wide variety of medium types. Common to all media and systems is the need to investigate and understand the effects of basic parameters such as anisotropy and grain size dispersion and the dispersion of easy axis orientation. While these parameters are less important for HAMR, they are still relevant for the long-term stability of recorded information which may be exacerbated by the increase of temperature resulting from the writing of neighbouring tracks.

The standard micromagnetic model is used to describe the magnetic properties and switching behaviour of PMR media. The micromagnetic model based on the stochastic-Landau-Lifshitz-Gilbert (LLG) equation [10, 11] is commonly used to study the switching behaviour of the magnetic recording layer during the recording process, and is limited to timescales of a few tens of nanoseconds due to the requirement of small timesteps. Moreover, the atomistic spin model [12] can be also used to study the information on the magnetisation reversal process and dynamics in the atomic detail. Although this gives physical insight, especially into the HAMR process, it is computationally limited to investigating the recording process on tens of grains. Here we are considering the quasi-static magnetisation processes taking place on timscales from microseconds to hundreds of seconds. The kinetic Monte Carlo method [13], although neglecting precession, is constructed for the range of timescales of concern in this work. Therefore, we use a granular micromagnetic model to investigate the magnetic properties of recording media in this work. The simulation is based on a kinetic Monte Carlo (kMC) approach in which the magnetostatic interaction and the intergranular exchange coupling are taken into account. In addition, the effect of easy axis distribution is also included. The effect of crucial parameters for thermal stability such as grain diameter, anisotropy constant, film thickness, easy axis distribution, and particularly grain size distribution are investigated. Calculations of magnetisation curves, the switching field, and the angular dependence on the critical field H_{cr} are presented to study the magnetic properties and reversal behaviour.

2. Model description

We have developed a granular micromagnetic model based on the kMC approach to theoretically investigate the effects of anisotropy dispersion and microstructure on the magnetisation reversal process in recording media with large perpendicular anisotropy. The aim is not to study the recording process itself: rather we are interested in the long-timescale (quasi-static) magnetisation processes which are used in the practical characterisation of the media. The kMC approach is necessary to access this timescale. Such a model is important for the characterisation of the media and also for the understanding of the long-term decay of written information. As a result our investigation is relevant to current perpendicular recording media and also to media for HAMR.

The model is based on kinetic Monte-Carlo (kMC) technique [14, 13]. The probability of grain switching is determined based on the Arrhenius-Néel relaxation time for stationary state. The free energy of magnetic system in form of Stoner-Wohlfarth theory [15] is dependent on the anisotropy constant K_U, grain volume V, and the total local magnetic field $\mathbf{H}_{\mathrm{T}} = \mathbf{H}_a + \mathbf{H}_{dip} + \mathbf{H}_{ex}$ where $\mathbf{H}_a$ is the external magnetic field applied for grain switching, $\mathbf{H}_{dip}$ is the magnetostatic field, and $\mathbf{H}_{\mathrm{ex}}$ is the intergranular exchange field which depends on the structure of the grains in the system, specifically the contact length between neighbouring grains and the cross-sectional area of a grain.

The calculation of the intergranular exchange interaction is presented in the work of Peng *et al.* [16]. Dispersion in the contact length and grain size results in a dispersion of the exchange field. Further details of $\mathbf{H}_{dip}$ calculations can be found in Refs. [14, 13]. Therefore, All magnetic grains have an intrinsic energy barrier written as the following equation

$$E = K_U V(\mathbf{e}\cdot\mathbf{m})^2 - \boldsymbol{\mu}\cdot\mathbf{H}_\mathrm{T}, \tag{1}$$

where, the unit vectors **e** and **m** are the direction of the easy axis and the magnetisation, respectively. $\boldsymbol{\mu}$ represents the magnetic moment of each grain.

In the kMC approach the switching probability is dependent on the measuring time t_m which is the time used to measure the magnetization at each field as follow,

$$P_t = 1 - e^{-t_m/\tau}, \tag{2}$$

where, the relaxation time τ is given by the Arrhenius-Néel law

$$\tau^{-1} = f_0 \exp(-\Delta E/k_B T). \tag{3}$$

Here, f_0 is an attempt frequency and ΔE is the energy barrier. Typically, large energy barriers of $> 60 k_B T$ are required in order to ensure long-term thermal stability of written bits.

We now consider the effect of the misorientation of the magnetic easy axes. Easy axes are chosen randomly within a Gaussian dispersion of angle about the normal. The total energy barrier including the effect of anisotropy dispersion can be written as

$$E_b(\mathbf{H}_\mathrm{T},\psi) = K_U V[1 - \mathbf{H}_\mathrm{T}/g(\psi)]^{\kappa(\psi)}, \tag{4}$$

where $g(\psi) = [\cos^{2/3}\psi + \sin^{2/3}\psi]^{-3/2}$ and $\kappa(\psi) = 0.86 + 1.14g(\psi)$ are the numerical parameters given by Pfeiffer [17] where ψ is the easy axis orientation with respect to the total field ($\mathbf{H}_\mathrm{T}$).

The kMC algorithm is applied to evaluate the time evolution of the magnetisation by calculation of the transition probability in equation 2. The energy barrier in equation 4 for all grains is calculated at each field step to investigate the relaxation time in order to consider the transition rate between the two minima energy states $\tau^{-1} = \tau_{12}^{-1} + \tau_{21}^{-1}$. For transition probability, a random number, x $(0 < x < 1)$ is generated to determine the reversal probability of each grain. if $P_t > x$, the reversal of magnetisation is allowed whereas if $P_t < x$, the grain remains in its current minimum. It is noted that the rate dependence of the coercivity, H_c can be obtained by varying the timestep in the hysteresis loop calculation.

In order to construct a realistic media microstructure, it is important to simulate the physical structure of magnetic grains by including the non-magnetic grain boundaries [18]. In previous work [3, 19], we experimentally presented the transmission electron microscopy magnetic grain images of advanced PMR media including exchange coupled composite (ECC) media and continuous granular composite (CGC) media. We found that the microstructure of advanced PMR media depending on the detail of the sputtering process. The grain structure is created using the Voronoi construction. The process starts with seed points on a regular hexagonal grid. These points are moved randomly by a maximum distance δ, which determines the degree of order of the lattice and the dispersion of the grain size. The distribution of grain size produced by this process is close to lognormal, in agreement with experiment [3]. A calibration curve of the standard deviation of the lognormal distribution, σ_{lnD} as a function of the value of the maximum distance, δ is calculated and used to determine the input value of δ for a given required σ_{lnD}.

Figure 1 shows the typical different physical structure from Voronoi construction comparing with the bright field in-plane TEM images of the advanced recording media from refs [3, 19]. For small δ, the Voronoi construction creates a uniform structure close to that of a realistic ECC/CGC medium as shown in Fig.1(a). Meanwhile, the Voronoi construction can also create a more distorted structure as shown in Fig.1(b). In this work, we generate a series of microstructures with specified grain size and size distribution as found in realistic recording media [14, 20, 21, 22].

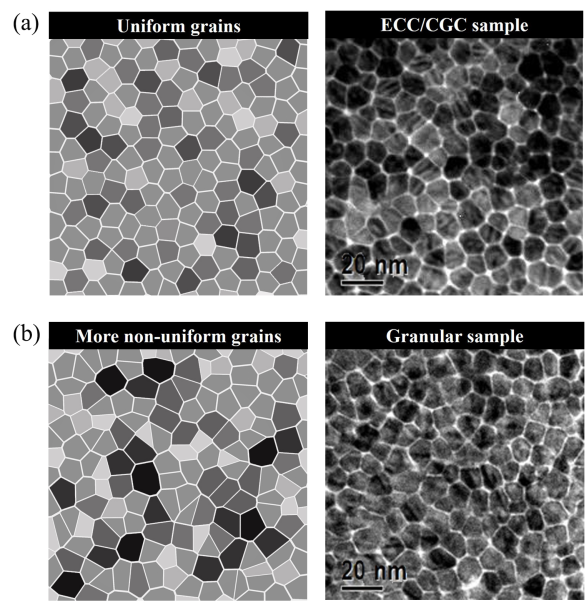

Figure 1. (Color online) the comparison of physical microstructure between Voronoi construction and bright field in-plane TEM image of advanced PMR media [19]: a) uniform magnetic grains system and b) more non-uniform magnetic grains system.

Here, we consider specifically a CoPt-based alloy [12], although the model is also applicable to the static properties often used to characterise HAMR media. We study a system with uniform grain size distribution. The lateral system size of the film is fixed at 200 nm with the median grain diameter (D_m) of 6 nm with a film thickness of 10 nm. It is noted that the soft magnetic underlayer (SUL) is not included into kMC calculation due to the fact that the recording layer and SUL are separated by the thick seed layer which is to prevent intergranular exchange coupling in the recording layer via SUL.

3. Results

We have applied the granular model of recording media to investigate the magnetic properties and in particular the effects of anisotropy dispersion and the microstructural design such as magnetic grain size, film thickness and grain size distribution. The results are of interest for the investigation of both the commonly magnetic materials as CoPt-alloy used in current recording technologies [12] for media and HAMR applications. Moreover, the magnetisation reversal behaviour is also investigated as a function of the film thickness via the angular dependence of the critical field, $H_{cr}(\theta)$ in order to understand the reversal mechanism of advanced media for PMR and HAMR technology. It is noted that the measuring time is set to 0.1 second per field step where the sweep rate of all calculations is 2500 Oe/s.

The different physical structures are generated via Voronoi construction within a computational cell having a lateral size of 200 nm^2. The magnetic parameters of CoPt alloy used in this kMC simulation are Curie temperature, T_c = 700 K [23], the saturation magnetisation, M_s = 600 emu/cc [24], and $K_U = 1 \times 10^7$ erg/cc [24, 25]. All simulations are performed at 300 K. The calculation results are separated into three main parts which will be discussed in detail as follows.

3.1. Effect of physical microstructures

The effects of physical microstructure on the magnetic properties of PMR media with varying grain size (D_m), grain size distribution, and film thickness (t_{film}) are considered. For realistic calculation, the magnetostatic and intergranular exchange interactions are included into kMC model. Further details of both $\mathbf{H}_{dip}$ and $\mathbf{H}_{ex}$ can be found in Ref.[14]. The effect of grain size is firstly investigated by varying the diameter from 4 nm to 16 nm with a diameter step of 2 nm. In our previous work [14], we proposed a two-stage fitting procedure to extract the exchange field and easy axis dispersion from advanced PMR media. We found that an exchange field of 2 kOe was a reasonable value for the current recording media. Therefore, the intergranular exchange field strength (H_{exch}) between grains is fixed as 2 kOe unless indicated otherwise. It is noted that the effect of the easy axis distribution ($\sigma_\phi = 0°$) is not considered and the grain size distribution is generated as uniform magnetic grains for this case study.

The typical normalizated half hysteresis loops with variation of median grain diameter at fixed film thickness of 10 nm have been calculated using the kMC micromagnetic model as depicted in Fig.2 (a). The result shows that the value of coercivity field (H_c) is gradually reduced by decreasing the grain diameter. Meanwhile, grain diameters less than 6 nm shows the transition to unstable or superparamagnetic behavior of the media, with the remanence value (M$_R$) decreasing more than 50 %. Interestingly, we also found that the slope of the normalized magnetisation curve at the H_c is steeper with increasing grain diameter although the exchange interaction is fixed at 2 kOe (weak exchange). Further, we now proceed to investigate the change of the slope of magnetisation curve at H_c due to the effect of strong exchange interaction (8 kOe). The half hysteresis loop with the grain size dependence is presented as shown in Fig.2 (b). It is clearly seen that for large grain diameter (> 10 nm) with the increased exchange interaction affects only the coercivity but not the form of the magnetisation curve as shown in Figure 2 (b). This is probably due to the fact that the magnetic system with larger grain diameter is already highly thermally stable which means that the exchange will tend to shift rather than enhance the energy barriers.

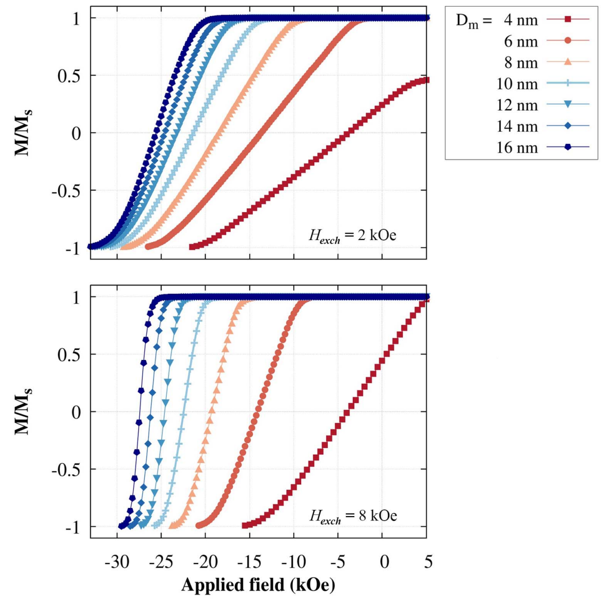

Figure 2. (Color online) Half hysteresis of CoPt alloy for different median grain diameters at (a) H_{exch}= 2 kOe (weak exchange) and (b) H_{exch}= 8 kOe (high exchange).

One of the most crucial parameters for enhancing the performance of advanced recording media is the switching field distribution which originates from several factors, in particular the grain size distribution. The well-isolated grains segregated by the silicon oxide with small and uniform grain size distribution is required as bit-patterned media [26]. However, for conventional media the exchange coupling interaction between grains is still useful since it counterbalances the demagnetizing field. Hence, the effect of the uniformity of magnetic grains, which is a large contribution to the dispersion of the exchange field,

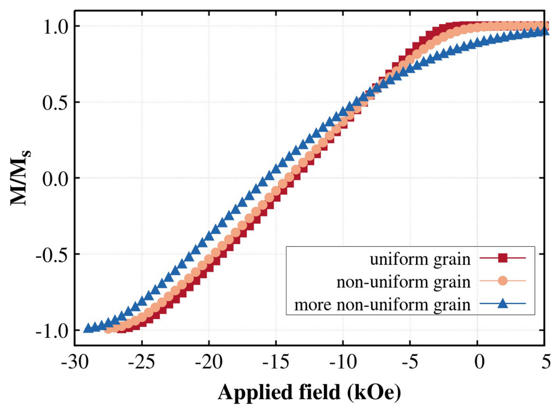

Figure 3. (Color online) Half hysteresis of CoPt alloy for various value of grain size distribution including the effect of intergranular exchange field coupling at H_{exch}= 2 kOe.

on the magnetic properties is also investigated. In order to investigate the effect of grain size distribution on the switching process, the microstructures for different media types as discussed earlier are constructed by Voronoi construction. Here, the dispersion of grain size is defined by using the variation of the standard deviation σ_{lnD} obtained from the distance to move δ as described in Sec.II. The standard deviations of the lognormal distribution σ_{lnD} are controlled at 0.05, 0.15 and 0.3 for the different microstructure as uniform, non-uniform and more non-uniform respectively.

In this study the grain diameter and film thickness are fixed at 6 nm and 10 nm respectively with H_{exch}= 2 kOe. The magnetisation curves with varying grain size distributions are compared as depicted in Fig.3. The result shows that the tendency of M-H loop almost superimpose for the uniform and non-uniform systems whereas the more non-uniform system shows the reductions of the M-H slope leading to increased SFD and also reduction of M_R and the nucleation field (H_n) at which the magnetisation starts to reverse. This is possibly due to the increased distribution of energy barriers arising from the distortion of each grain in the system.

We now also proceed to investigate the effect of the uniformity of grain structure on H_c with different values of exchange field H_{exch} which is varied from 1 kOe to 5 kOe with a field step of 1 kOe. Fig.4 shows the variation of H_c as a function of H_{exch} for the different distribution of magnetic grains. Firstly we note that the coercivity increases with increasing disorder. This is consistent with the results of Peng et. al [16], who show that the increase of disorder leads to effective pinning sites which increase the coercivity. Although the decrease in H_c is monotonic for the most non-uniform (highly disordered) case, the variation of H_c with exchange field is weaker for the uniform and non-uniform cases with a slight increase for large exchange. This could be due to the increasingly stabilising effect of the large exchange field for these cases. This confirms the significant effect of the exchange interaction and the microstructure on the switching process.

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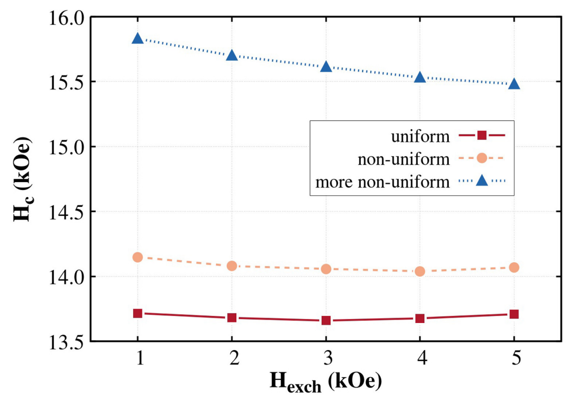

Figure 4. (Color online) The effect of intergranular exchange field on coercivity as a function of grain size distribution.

3.2. Angular dependence of H_{cr}

In order to understand the magnetisation reversal behavior for advanced recording media with small grain size, the angular dependence of the critical field, H_{cr} [12] as a function of film thickness is investigated, including the magnetostatic field, intergranular exchange field and the thermal effects at room temperature 300 K. Moreover, the easy axis dispersion expected to affected the magnetisation reversal behavior is also studied. In order to determine the effect of easy axis distribution, the comparison angular dependence of H_{cr} at the perfect alignment case, $\sigma_\phi = 0°$ and small easy axis distribution, $\sigma_\phi = 3°$ is performed as Figure 5. The definition of the critical field is the field at which the magnetisation irreversibly flips between two stable states of the energy surface.

The smallest grain diameter is fixed at 6 nm to remove superparamagnetic behaviour. The effect of film thickness is investigated varied in the range 4 nm to 14 nm. The variation of H_{cr} as a function of applied field angle θ from the film normal ranges from 0° to 60°. The angular dependence of $H_{cr}(\theta)$ normalized by $H_{cr}(\theta = 0)$ is calculated at 300 K and σ_ϕ at 0° and 3° in order to include the effects of thermal activation and easy axis distribution respectively on the reversal behavior. Fig.5 (a) and (b) show the angular dependence of the critical field as a function of the film thickness in order to understand the effect of the physical structure on the magnetisation reversal mechanism at σ_ϕ = 0° and 3° respectively. The coherent magnetisation reversal can be indicated from the minimum field angle at θ = 45° corresponding to the Stoner-Wohlfarth theory [15].

We found that the inclusion of easy axis distribution does not affect the curve of the angular dependence of H_{cr} and the magnetisation reversal behavior especially at the thick film. But it obviously causes the sharp of the variation of H_{cr} at thin thickness 4 nm as shown in Fig.5 (a) and (b). For the thick film of 14 nm, it is obviously seen that the minimum value of H_{cr} is 0.5 of $H_{cr}(0)$ at 45° which is similar trend of the Stoner-Wohlfarth behavior [15]. This behavior exhibits the coherent magnetisation reversal process which implies the individual switching of each grains for thick film. Meanwhile, the trends of angular dependence of H_{cr} for decreasing film thickness show a deviation from the coherent reversal behavior. The minimum switching field angle is shifted to 30° when the film thickness reduces down to 4 nm as shown in the inset. This shows that the reduction of film thickness results in more complex reversal processes. It is due to increasing thermal instability or perhaps more importance of the interactions. Interestingly, our result shows similar behavior to experimental work reported by Morrison *et.al.* in Ref. [27].

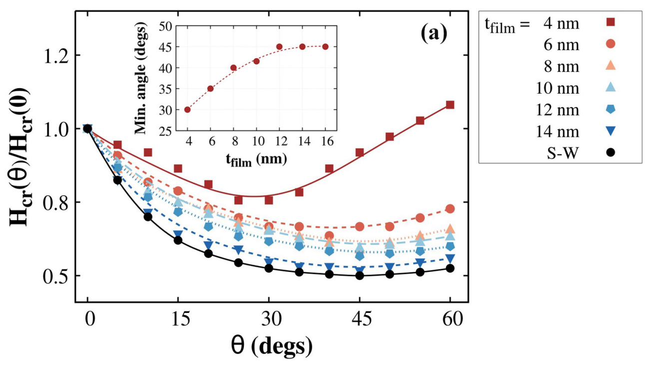

Figure 5. (Color online) The angular dependence of H_{cr} on the variation of film thickness comparing with S-W theory. The inset gives the minimum angle of H_{cr} as a function of the film thickness.

3.3. Effect of easy axis distribution

The switching field distribution is a significant factor impacting the performance of advanced recording media. The main contributions to the SFD originate from the easy axis distribution and the crystalline anisotropy constant. A small dispersion of easy axis orientation leads to a rapid reduction of the switching field according to Stoner-Wohlfarth theory [15]. We now consider the combined effects of the easy axis dispersion and the crystalline anisotropy constant on magnetic properties in particular the value of coercivity. A uniform grain size system with diameter of 6 nm and film thickness of 10 nm is investigated. The coercivity is calculated as a function of the magnetic anisotropy constant varied from 9×10^6 erg/cc to 1.4×10^7 erg/cc for various easy axis dispersion (σ_ϕ) from 0 ° to 8°

Figure 6 (a) shows the variation of H_c as a function of the anisotropy constant and dispersion of easy axis orientation. The result shows an increase of H_c with K_U for all cases of the dispersion. Moreover, the value of H_c as a function of K_U for perfect alignment case, $\sigma_\phi = 0°$ is maximal. Interestingly, it is found that the slope of H_c as a function of K_U slightly decreases with increasing dispersion of easy axis orientation from 0° to 8°. The intrinsic switching field is often described as $H_K = \alpha K_U/M_S$ where α is a factor characterising, among other parameters, the orientation of the grains. Our results show a decrease of α from 1.40 to 1.04 with increasing easy axis dispersion. This is consistent with theory, where the value of α (uniaxial anisotropy) varies from 0.96 to 2 for the dispersion of easy axis orientation varying from 3D random to perfect alignment [28]. Interestingly, the easy axis dispersion does not significantly affect the shape of the hysteresis loop as shown in the inset of figure 6 (a). The variation of H_c as a function of easy axis dispersion for various values of K_U is shown in Fig. 6 (b). It is found that the coercivity initially reduces rapidly with easy axis dispersion for all cases, leading to an asymptotic value: behaviour consistent with the angular dependence of the Stoner-Wohlfarth theory [15]. Our results also show similar trends to those reported by Lee *et. al.*[29]. Clearly the easy axis distribution strongly affects the magnetic properties, especially the switching field of material which are candidates for the advanced recording media including HAMR and Microwave Assisted Magnetic Recording (MAMR) technologies.

3.4. Time dependence of the switching field

We have also studied the effect of time dependence of the coercivity H_c of recording media with high magnetic anisotropy material. In practice, the thermal stability factor $\triangle E \sim K_U V/k_B T$ must be > 60 to ensure thermal stability of written information. During the magnetic hysteresis process, thermal activation drives the magnetisation reversal process, leading to the observed time and temperature dependence of H_c. For a system of identical non-interacting grains the time and temperature dependence can be described by the well-known Sharrock equation [30, 31] as

$$H_c(t) = H_K\left\{1 - \left[\frac{k_B T}{K_U V}\ln\left(\frac{f_0 t}{\ln 2}\right)\right]^n\right\}, \quad (5)$$

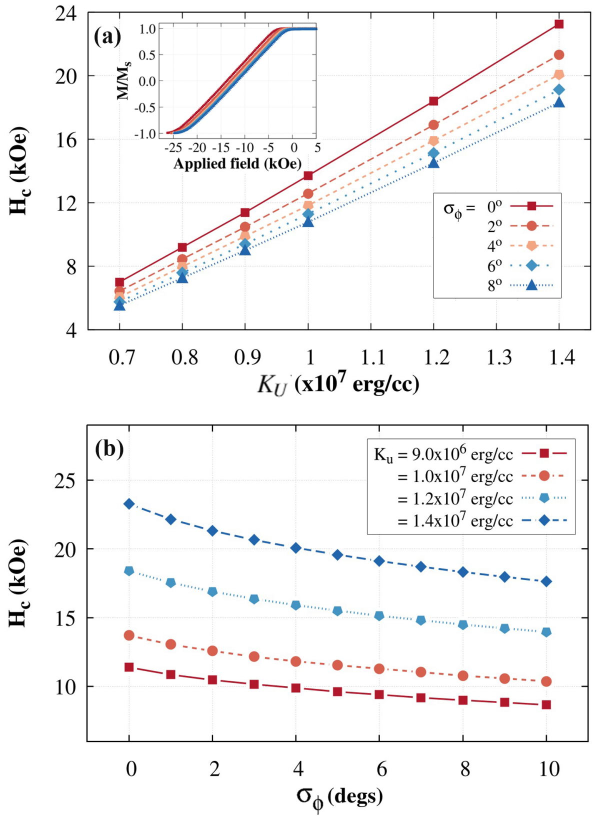

Figure 6. (Color online) Coercivity as a function of (a) anisotropy constant with the presence of shape of half hysteresis loop as an inset and (b) orientations of easy axis relative to the applied field.

where, $H_c(t)$ is the dynamic coercivity for a measurement time or MH loop time (t), H_K is the anisotropy field, $2K_U/M_S$, V is the grain volume, f_o is an attempt frequency and the exponent n relates to the easy axis distribution [31, 32]. Fitting the Sharrock law to experiment is a commonly used technique to determine the stability factor $\triangle E \sim K_U V/k_B T$ and an effective value for H_K. Here we investigate the effect of the easy axis dispersion on the Sharrock law and relate this to the exponent n.

The kMC model is used to characterize the long-term decay of writing process by calculating the variation of H_c as a function of measuring time ranging from 0.1 s to 10^9 s. This is related to the sweep rate of 2500 Oe/s - 2.5×10^{-7} Oe/s. The system has a grain size dispersion and a Gaussian easy axis distribution with a standard deviation of 3 degrees. The external field is applied normal to the plane at 300 K. The coercivity is calculated as a function of measurement time as shown in Fig.7. The calculated results exhibit the expected significant reduction of H_c with increasing measurement time on a logarithmic timescale.

The predicted coercivity is fitted to the Sharrock equation as shown in Fig.7. In the fact, the writing process in magnetic recording media operates at extremely short time (less than 0.1 ns) or high frequency at gigahertz [31, 33]. Therefore, The attempt frequency used in this calculation is 10^{10} Hz due to the high anisotropy [31, 33]. In addition, the the stability factor $\triangle E \sim K_U V/k_B T = 68$, sufficient to ensure long-term thermal stability of written bits. The time dependence of H_c from Sharrock's equation is calculated and fitted to the dynamic of coercivity from kMC model. We found that the exponent n is a critical parameter which affects the behaviour of time dependence of the H_c. Figure 7 shows that the time dependence of the coercivity from the kMC model is in excellent agreement with the Sharrock law assuming an exponent $n = 0.3$. However, the value of the exponent n is slightly smaller the expected value from Stoner-Wohlfarth theory ($n = 0.5$ [34]) for perpendicular recording media assuming that the preferred axis is parallel to the direction of the applied field. This may arise due to the effects of the dispersion of easy axes and/or the intergranular interactions. However, we note that Victora [32] shows that an easy axis dispersion leads to an increase in the exponent n, which suggests that the interparticle interactions are the dominant factor.

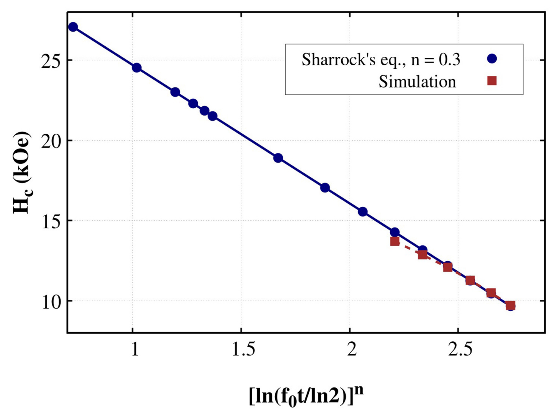

Figure 7. (Color online) The variation of switching field as a function of measuring times in logarithm scale comparing between Sharrock's equation and the simulation result: line is a guide to the eyes.

4. Conclusions

In conclusion, we have investigated the quasi-static magnetic properties of high anisotropy thin films for application as advanced recording media. To cover the timescales involved we used a micromagnetic model based on the kinetic Monte Carlo method. A realistic physical structure of the medium was generated using a Voronoi construction which allowed control of the uniformity of magnetic grains and grain size dispersion. The effects of intergranular exchange coupling, magnetostatic field and the distribution of easy axis orientation are taken into account. These are all important contributions to the magnetic properties and magnetisation reversal behavior in experiments often used for the characterisation of practical, media.

We found that the criterion of the smallest grain diameter for anisotropy values of 10^7 erg/cc is 6 nm which presents the stable state for typical CoPt-alloys. The intergranular exchange coupling is found to be an especially important stabilising factor for small grain size. We also considered the uniformity of grain structure on magnetic properties in particular the switching field. the non-uniformity of the magnetic grains gives rise to non-monotonic behavior of H_c with increasing exchange field. Moreover, we found, by investigating the variation of switching field with angle that the microstructure strongly affects the variation of the magnetisation reversal mechanism with the decreasing film thickness. The minimum switching field angle is shifted from 45° to 30°. Finally, we investigated the time dependence of the coercivity. We found that the Sharrock law fitted the model results well, but with a reduced value of the exponent n. It was argued that this most likely arises from the effect of the intergranular interactions, which are therefore an important factor in interpreting the the values of the thermal stability factor $\triangle E \sim K_U V k_B T$ obtained from dynamic coercivity experiments. Although, the calculations were performed specifically for PMR media it is equally valid for microwave assisted and heat assisted recording media technologies. These also require advanced characterisation methods and the kMC model developed here is an important tool for the understanding and development of such techniques, especially given the importance of understanding the thermal decay of information as grain sizes are reduced.

ACKNOWLEDGEMENTS

This research was financially supported by Mahasarakham University research support and development fund.

References

[1] Piramanayagam S N and Srinivasan K 2009 *Journal of Magnetism and Magnetic Materials* **321** 485–494

[2] Chureemart J, Chureemart P, Evans R, Chantrell R W and O'Grady K 2011 *Journal of Physics D: Applied Physics* **44** 455002

[3] Chureemart J, Lari L, Nolan T P and O'Grady K 2013 *Journal of Applied Physics* **114** 083907

[4] Olson T, Lengsfield B, Parker G, Shiimoto M, Sugiyama M and Xu L 2016 *IEEE Transactions on Magnetics* **52** 1–8

[5] Allen D G, Baer A, Feldbaum M, Guthrie H C, Hsiao W C D, Hsu Y, Jiang M, Liu Y, Neuhaus A, Nikitin V *et al.* 2009 Perpendicular magnetic write head having a magnetic write pole with a concave trailing edge uS Patent 7,576,951

[6] Piramanayagam S N 2007 *Journal of Applied Physics* **102** 2

[7] Seigler M A, Challener W A, Gage E, Gokemeijer N, Ju G, Lu B, Pelhos K, Peng C, Rottmayer R E, Yang X *et al.* 2008 *Magnetics, IEEE Transactions on* **44** 119–124

[8] Weller D, Mosendz O, Parker G, Pisana S and Santos T S 2013 *physica status solidi (a)* **210** 1245–1260

[9] Bai X and Zhu J G 2017 *IEEE Transactions on Magnetics* **53** 1–5

[10] Torabi A F, Van Ek J, Champion E and Wang J 2009 *IEEE Transactions on Magnetics* **45** 3848–3850

[11] Nolan T P, Valcu B F and Richter H J 2010 *IEEE Transactions on Magnetics* **47** 63–68

[12] Chureemart P, Evans R, Chantrell R, Huang P W, Wang K, Ju G and Chureemart J 2017 *Physical Review Applied* **8** 024016

[13] Chantrell R W, Walmsley N, Gore J and Maylin M 2000 *Physical Review B* **63** 024410

[14] Chureemart P, Chureemart J and Chantrell R 2016 *Journal of Applied Physics* **119** 063903

[15] Stoner E C and Wohlfarth E P 1948 *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **240** 599–642

[16] Peng Y, Wu X, Pressesky J, Ju G, Scholz W and Chantrell R 2011 *Journal of Applied Physics* **109** 123907

[17] Pfeiffer H 1990 *physica status solidi (a)* **118** 295–306

[18] Srinivasan K, Piramanayagam S, Wong S K and Kay Y S 2008 *Journal of Applied Physics* **103** 7F512

[19] Chureemart J 2013 *Orientation and thermal stability of advanced recording media* Ph.D. thesis University of York

[20] Miles J J, Wdowin M, Oakley J and Middleton B K 1995 *IEEE transactions on magnetics* **31** 1013–1024

[21] Jones M and Miles J J 1997 *Journal of magnetism and magnetic materials* **171** 190–208

[22] Ye L, Pearson T, Dolbashian C, Pstrak P, Mohtasebzadeh A, Fellows B, Mefford O T and Crawford T M 2016 *Advanced Functional Materials* **26** 3983–3989

[23] Kashyap A, Garg K B, Solanki A K, Nautiyal T and Auluck S 1999 *Physical Review B* **60** 2262

[24] Jeong S, Hsu Y N, Laughlin D E and McHenry M E 2000 *IEEE transactions on magnetics* **36** 2336–2338

[25] Yuan F T, Sun A C, Huang C F and Hsu J H 2014 *Nanotechnology* **25** 165601

[26] Terris B D and Thomson T 2005 *Journal of physics D: Applied physics* **38** R199

[27] Morrison C, Saharan L, Ikeda Y, Takano K, Hrkac G and Thomson T 2013 *Journal of Physics D: Applied Physics* **46** 475002

[28] Luborsky F E 1961 *Journal of Applied Physics* **32** S171–S183

[29] Lee J, Brombacher C, Fidler J, Dymerska B, Suess D and Albrecht M 2011 *Applied Physics Letters* **99** 062505

[30] Sharrock M and McKinney J 1981 *IEEE Transactions on Magnetics* **17** 3020–3022

[31] Sharrock M 1994 *Journal of Applied Physics* **76** 6413–6418

[32] Victora R 1989 *Physical review letters* **63** 457

[33] Moser A, Takano K, Margulies D T, Albrecht M, Sonobe Y, Ikeda Y, Sun S and Fullerton E E 2002 *Journal of Physics D: Applied Physics* **35** R157

[34] Kitakami O, Shimatsu T, Okamoto S, Shimada Y and Aoi H 2003 *Japanese journal of applied physics* **43** L115